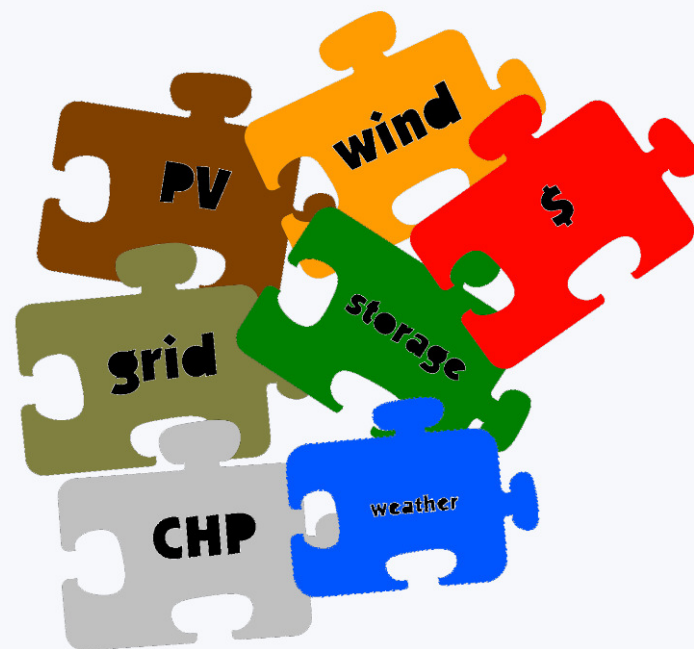


# Planning problems in grids with Distributed Energy Resources

KU Leuven, University of Leuven, Belgium  
<http://www.esat.kuleuven.be/electa>

Edwin Haesen  
Johan Driesen

- ✓ Introduction
- ✓ Problem Formulation
- ✓ Deterministic approach
- ✓ Evolutionary Algorithms
- ✓ Robust Multi-objective  
Planning Tool
- ✓ Test Cases
- ✓ Alternative grids
- ✓ Conclusion

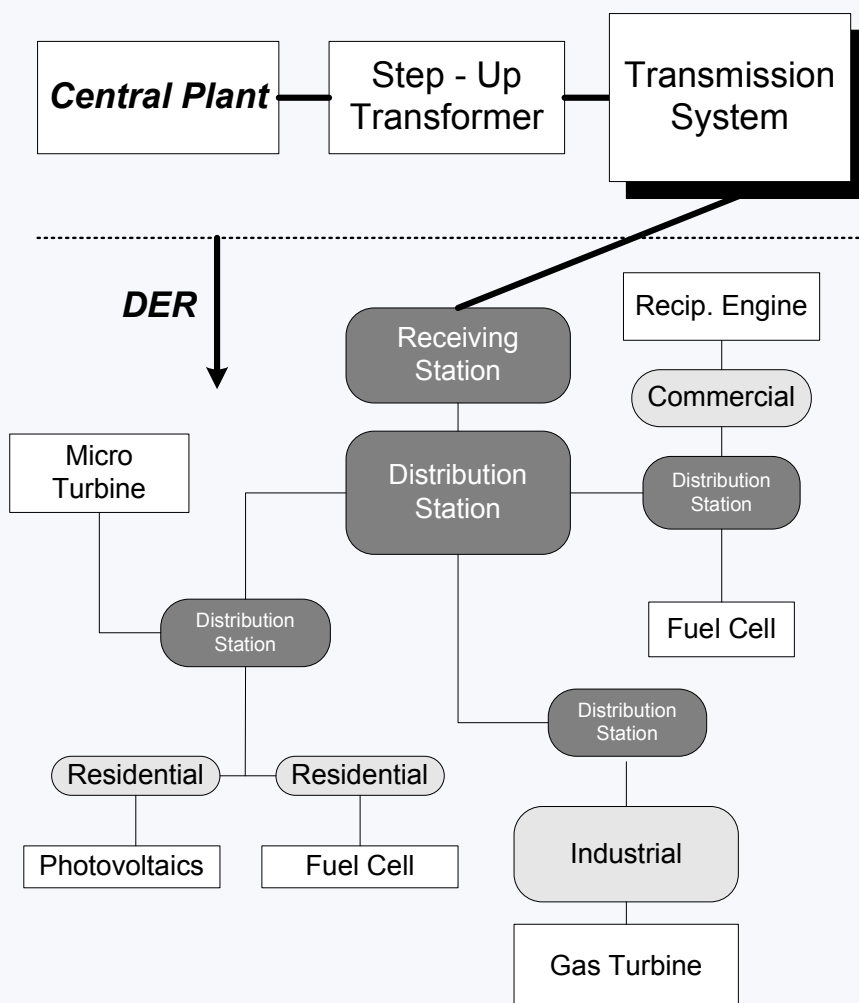


# Typical questions to solve



- Customer
    - ⇒ Which type/size of DG unit will make me the most money?
  - DSO
    - ⇒ How much DG can you put in a grid or feeder, without having to upgrade it?
    - ⇒ Benchmarking?
  - Utility
    - ⇒ When expanding: what is the best next spot for a DG unit?
  - Government
    - ⇒ Where to best spend those subsidies?
    - ⇒ Benchmarking?
  - Other
    - ⇒ Is this microgrid self-sustaining?
- ⇒ *economic + technical optimization problems*

# Planning problem



## ➔ What is the impact of a DER planning scheme?

- *Type of DER: renewable, CHP, diesel...*
- *Size of the unit*
- *Location in the grid*
- *Operation mode: peak shaving, market incentives, in coordination with storage...*

## ➔ Useful for

- *Customers: to improve self-sustainability*
- *Producers: as diversification of production park*
- *Grid operator or regulator: benchmarking*

## ➔ Multiple objectives

- *Technical: losses, stability, voltage profile, unbalance...*
- *Economic: investment, revenues...*
- *Risk-averse: deviations due to uncertain future fuel prices, weather conditions, load growth...*

# Problem Formulation

$V_{\text{node}} \leftarrow \text{flat profile}$

while  $\varepsilon > \varepsilon_{\text{max}}$

do {  
 $I_{\text{node}} = f_{\text{load model}}(S_{\text{node}}, S_{\text{DER}}, V_{\text{node}})$  (a)  
 $I_{\text{line}} = A \cdot I_{\text{node}}$  (b)  
 $V_{\text{node}} = V_{\text{grid}} - B \cdot I_{\text{line}}$  (c)  
 $\varepsilon = g_{\text{error}}(S_{\text{node}}, I_{\text{node}}, V_{\text{node}})$

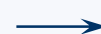
distribution system  
load flow equations



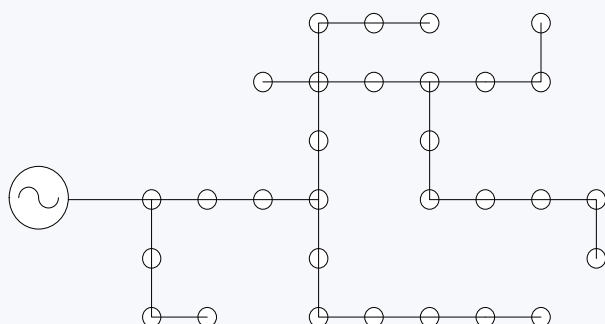
technical performance

- line losses
- voltage profile
- unbalance
- ...

non-linear load model



iterative procedure  
'backward-forward sweeps'



planning problem

- objective: e.g. line loss minimization
- variables: location & size of DER units
- constraints: budget & voltage deviations



nested optimizations in sweep algorithm

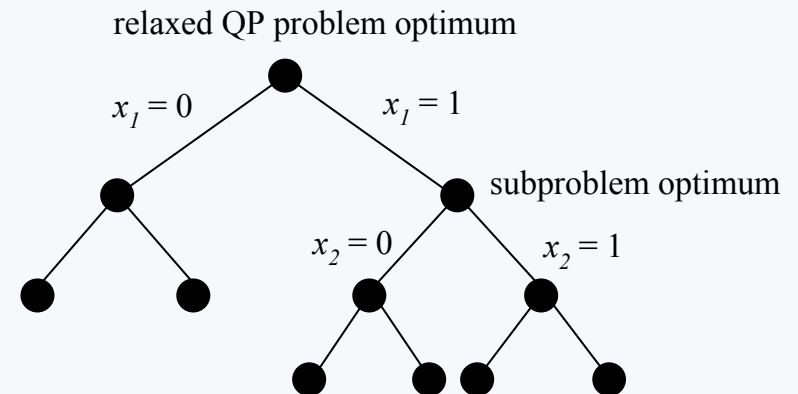
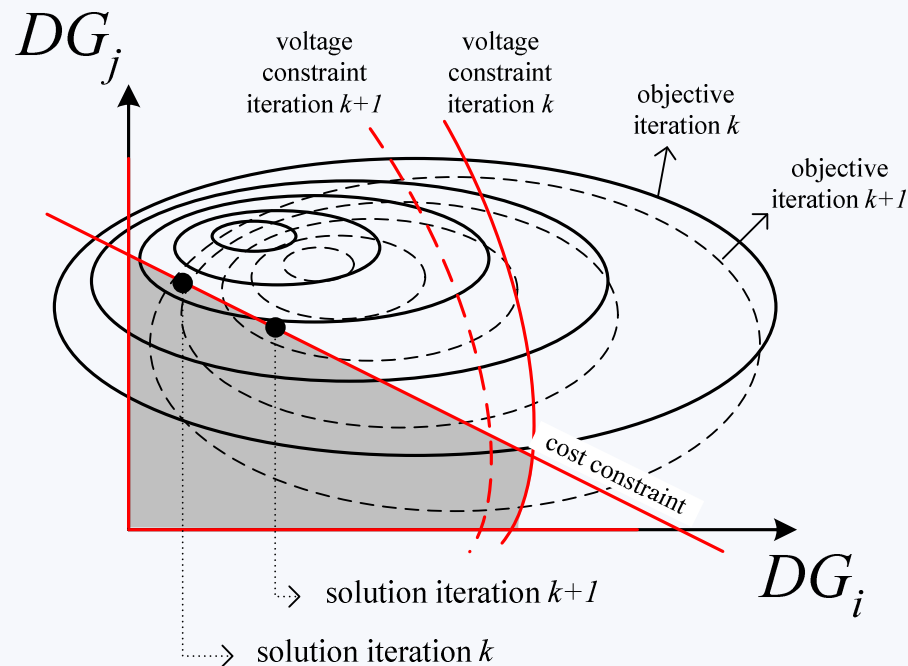
# Planning Issues: optimization example



Main problem (*non-linear*)

↩ Sequential quadratic optimizations (*MIQQ*)

↩ Branch and bound search across relaxed QP problems



## ⇒ Quadratic objective

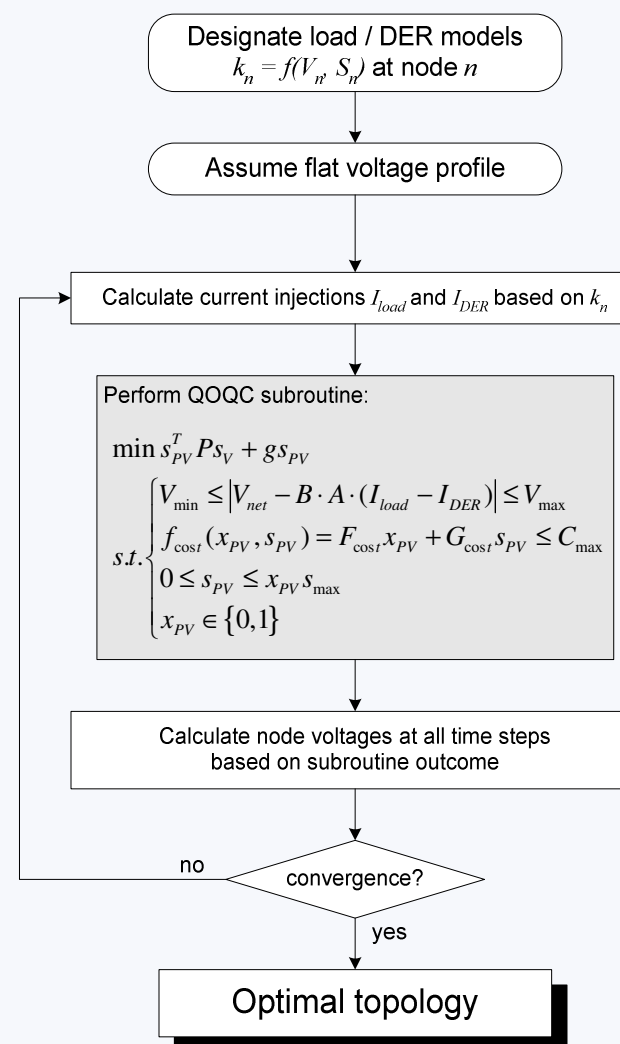
$RI^2 \rightarrow$  multiple nodes, DER types, time frames

## ⇒ Quadratic constraint

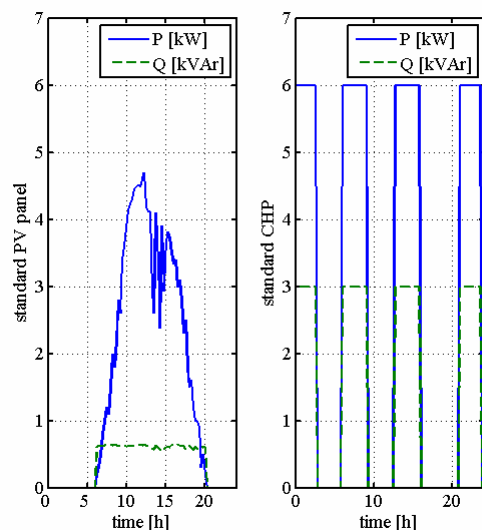
voltage amplitude

## ⇒ Integer variables

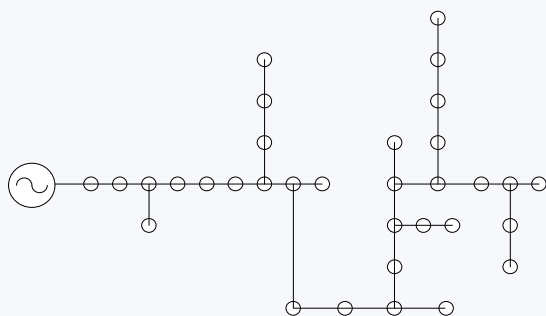
fixed cost, max #DER



iteration of MIQQ optimizations

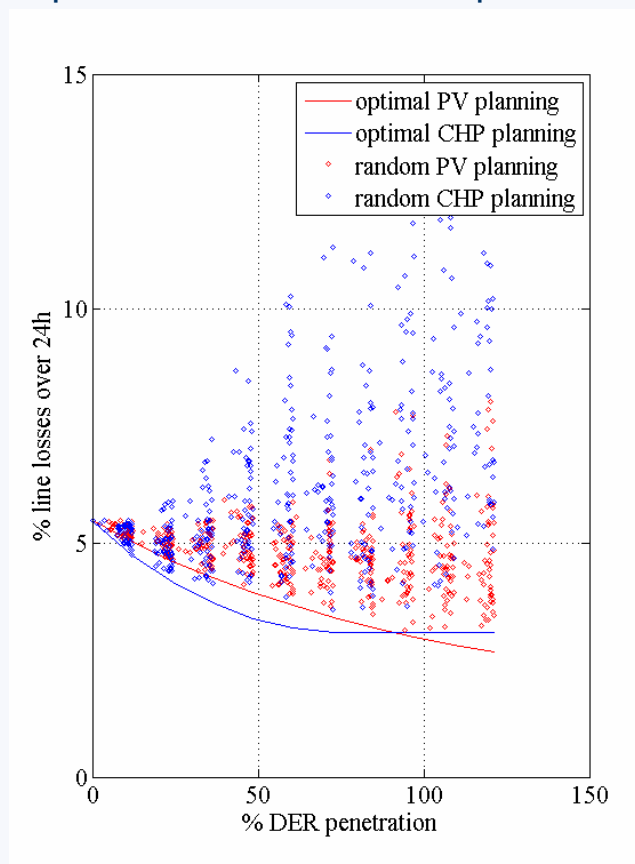


PV panel and CHP unit placement



IEEE 34-bus radial grid

optimal versus random placement

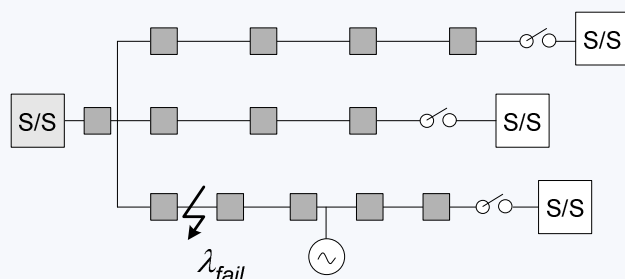


## Conclusions:

Random deployment: much higher losses  
 low %DER → grid support: best at end of feeders  
 high %DER → node support: relief high loads

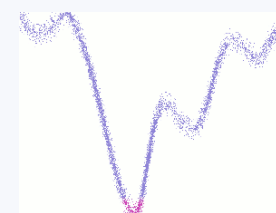


- Multiple objectives
- Complex objectives/constraints:  
**e.g. reliability enhancement, fault currents (urban areas),...**



SAIFI, SAIDI, CAIFI, CAIDI, ASAI, ASIFI, ASIDI, ...  
(IEEE1366)  $\Rightarrow$  which index? translated to cost?

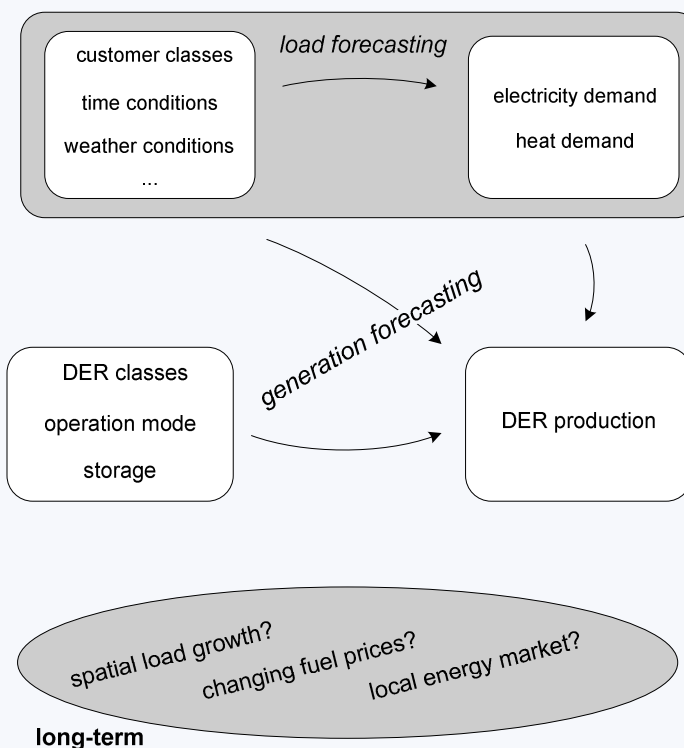
- What is known?
  - ✓ deterministic
  - ✓ stochastic  
**Load profiles, DG production, outages,...**
  - ✓ fuzzy  
**Voltage constraints ( $\Rightarrow$  EN50160?)**
  - ✓ uncertain  
**spatial load growth, regulation, ...**



$\Rightarrow$  A robust, multi-objective optimization is needed!

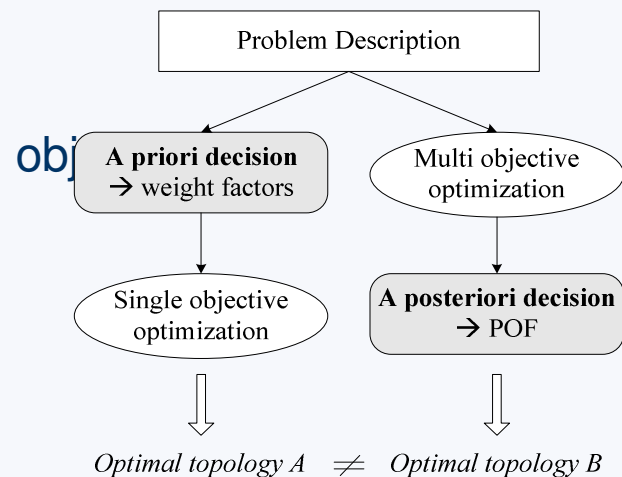
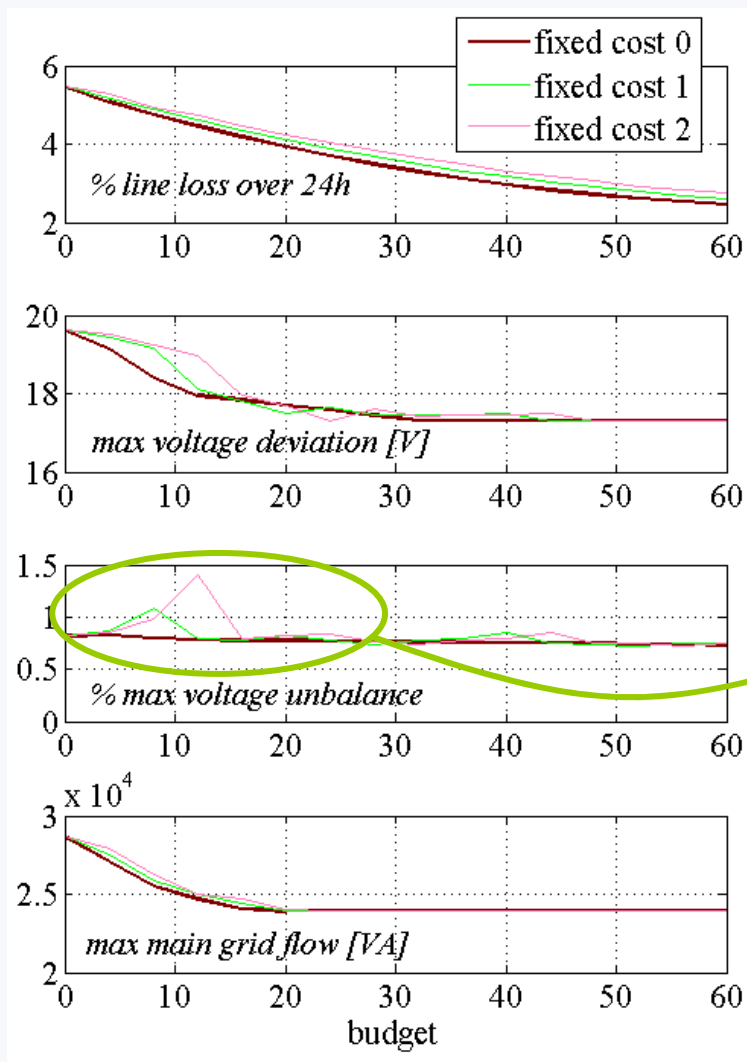
## Uncertainties remain...

- multiple objectives  
→ **acquire trade-off front**
- load models?  
→ **cause of non-linearity, but not the main uncertainty**
- load profiles, weather conditions, load growth, ...?



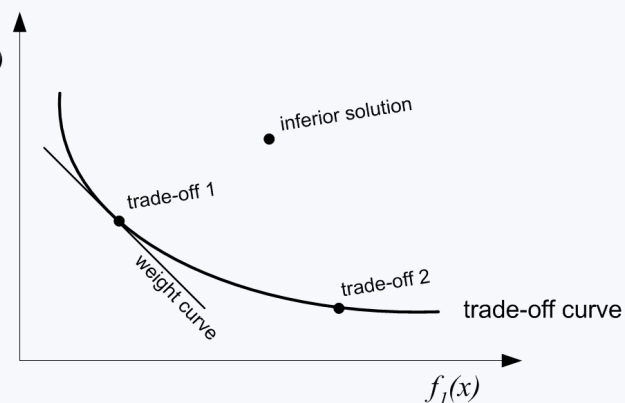
- ➔ Deterministic optimization obscures proper planning outcomes
- ➔ A robust, multi-objective optimization is needed

# Multiple Objectives



single phase DER

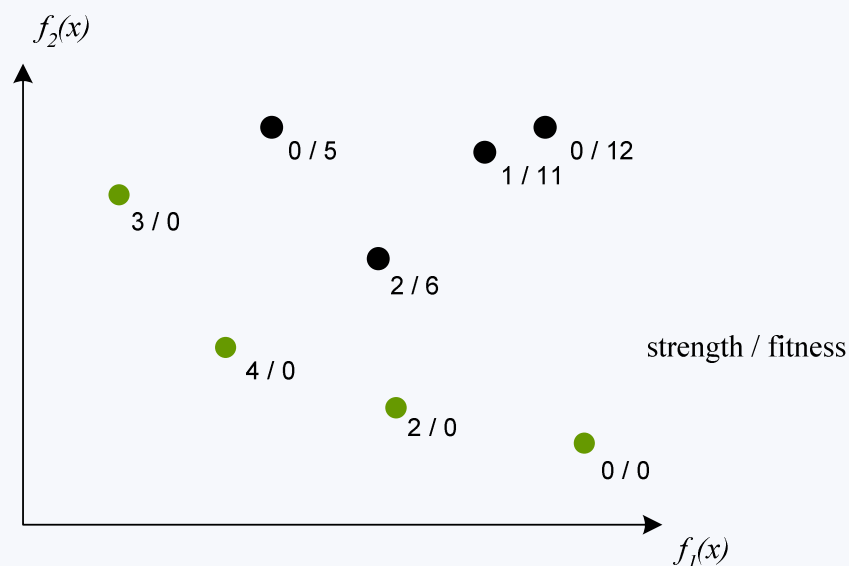
⇒ pc  $f_2(x)$   
⇒ ca

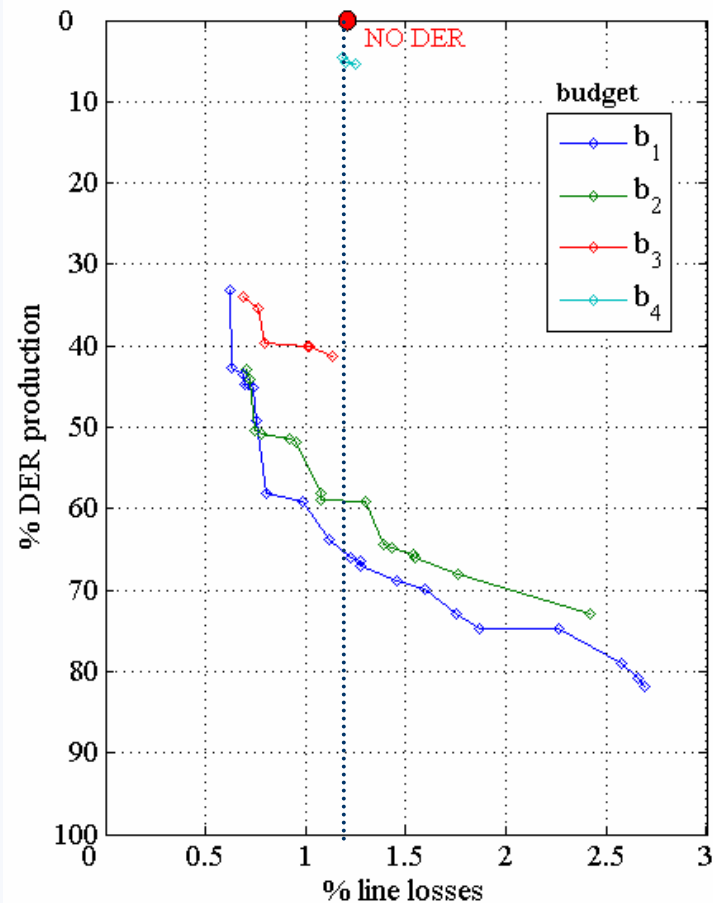


rt

## Pareto Strength

- No use of weight factors
- Search for non-dominated topologies = Pareto Optimal Front
- ➔ Pareto Strength = #dominated topologies
- ➔ Fitness = sum of Pareto Strengths of dominating topologies
- ➔ (Possible density adjustment)





## Placement

- PV panels
- micro-CHPs
- wind turbines

## Objectives

- Minimize line losses
- Maximize DER based energy production

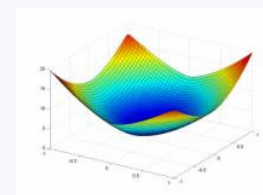
## Constraints

- $\Delta V$
- DER installation budget  
( $b_1 > b_2 > b_3 > b_4$ )

## (Non)-Convex?

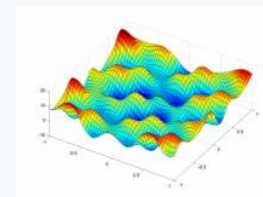
### Convex

- local optimum = global optimum
- reliable and efficient algorithms exist
- many apparent non-convex problems can be transformed into convex
  - » line loss minimization
  - » optimal microgrid configuration?

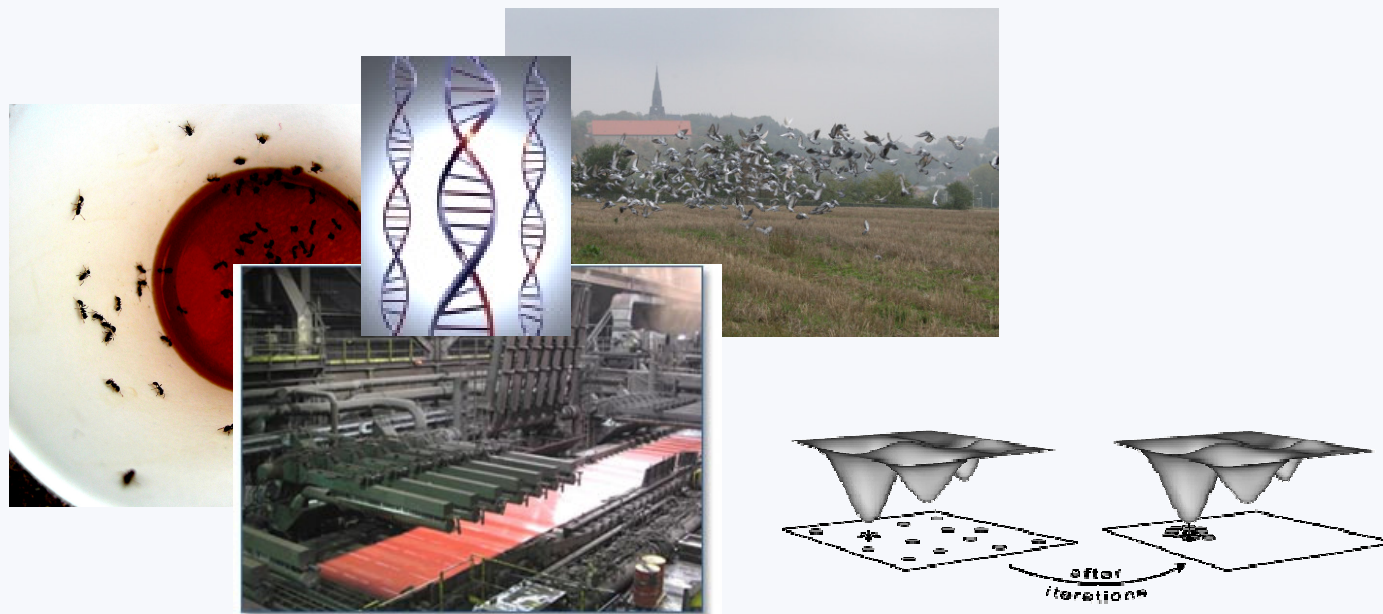


### Non-convex

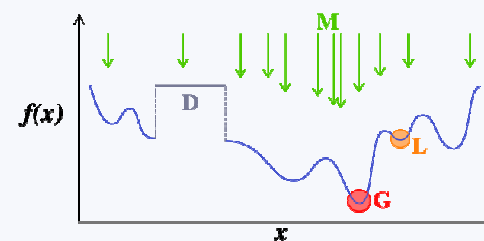
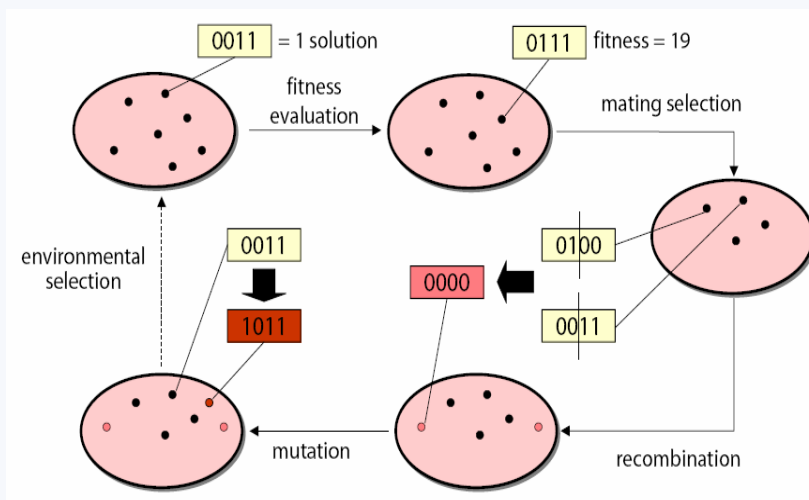
- application of evolutionary algorithms to search objective space
- non-guaranteed convergence
- high flexibility in function evaluation
  - ⇒ *can handle stochastic data*
- multi-objective algorithms
  - ⇒ *acquisition of all trade-offs in one run*



# Evolutionary Algorithms



## Genetic Algorithms



- Population based
- Transitions inspired by laws of biology
- Able to cope with complex problem formulations
  - No derivatives
  - Discontinuous functions
  - Multiple objectives
  - Stochastic formulation
- No guaranteed convergence to global optimum
- Mathematical foundation?

## Simulated Annealing

produce variations  $j$  & lower temperature  $c$

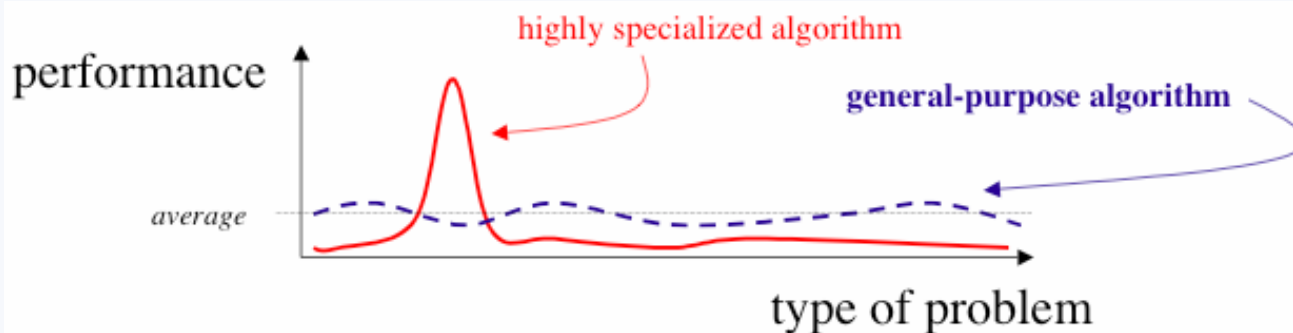
$$\mathbb{P}_c(\text{accept}(j)) = \begin{cases} 1 & \text{if } f(j) \leq f(i) \\ e^{-\frac{f(i)-f(j)}{c}} & \text{if } f(i) < f(j) \end{cases}$$

## Particle Swarm, Ant colony, Tabu search, ...





*“There ain’t no such thing  
as a free lunch”*



no indication EAs are less reliable

planning procedure has to be problem specific !!

## Multiple Objectives

### ➤ Aggregation

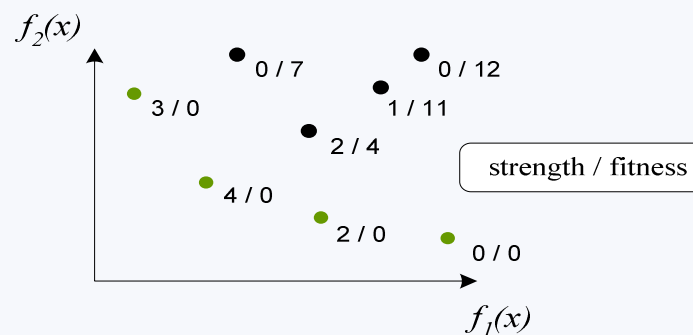
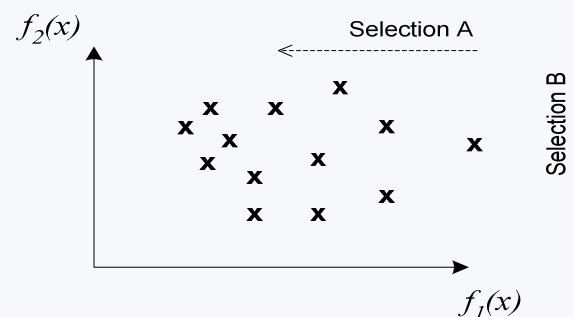
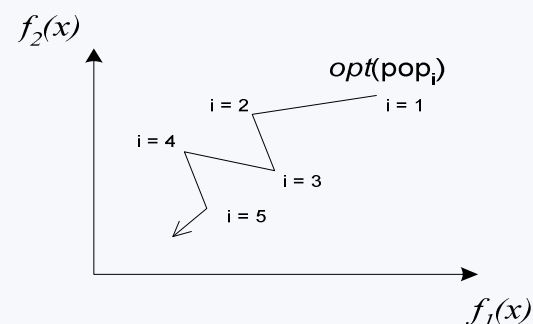
$\varepsilon$  - constrained

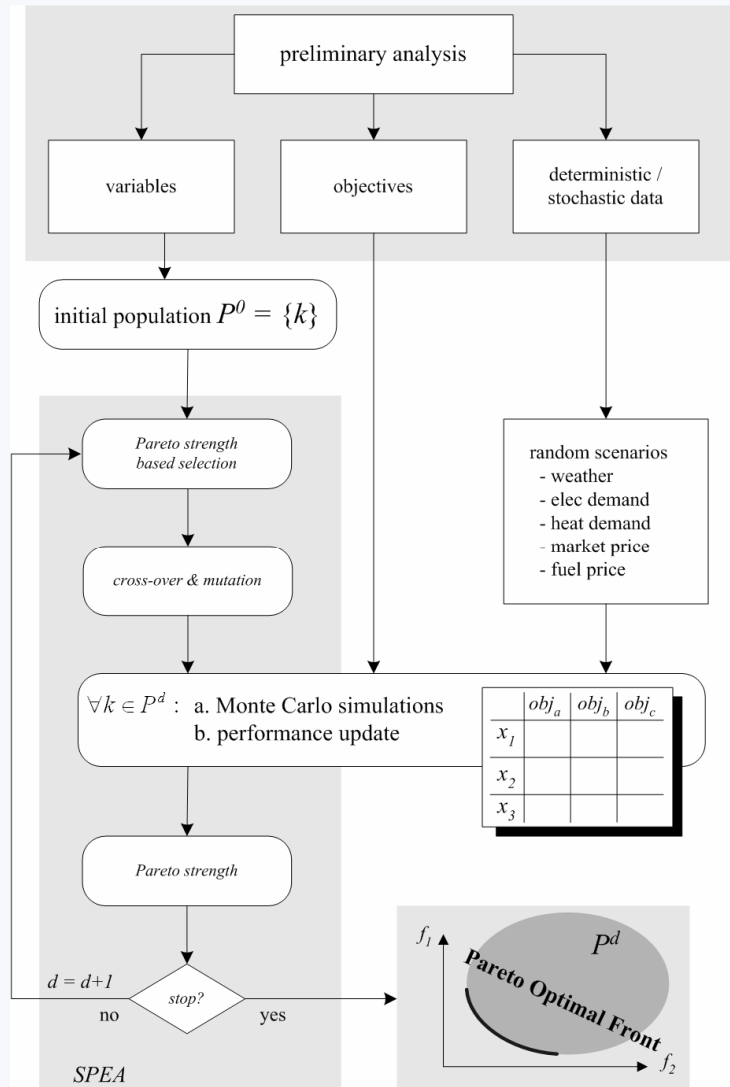
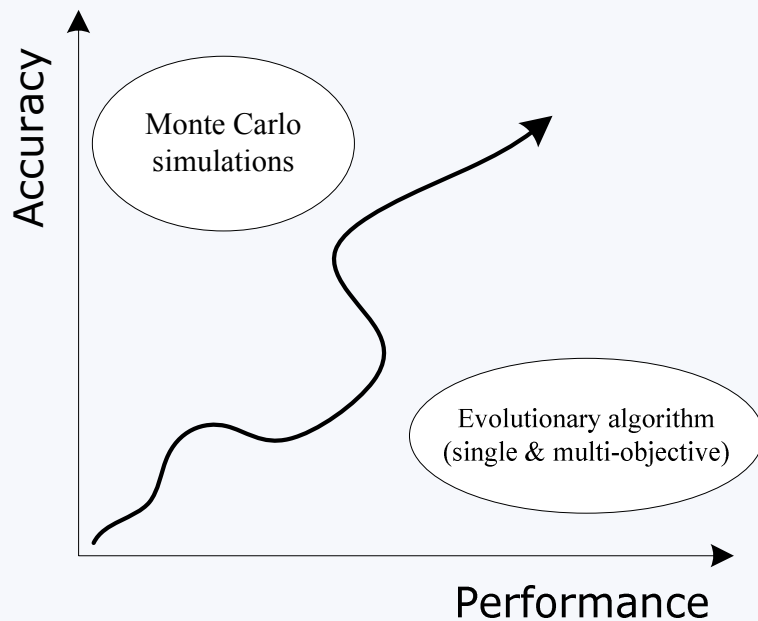
*parameter-oriented*  
*scaling-dependent*

### ➤ Vector evaluation alternating objectives

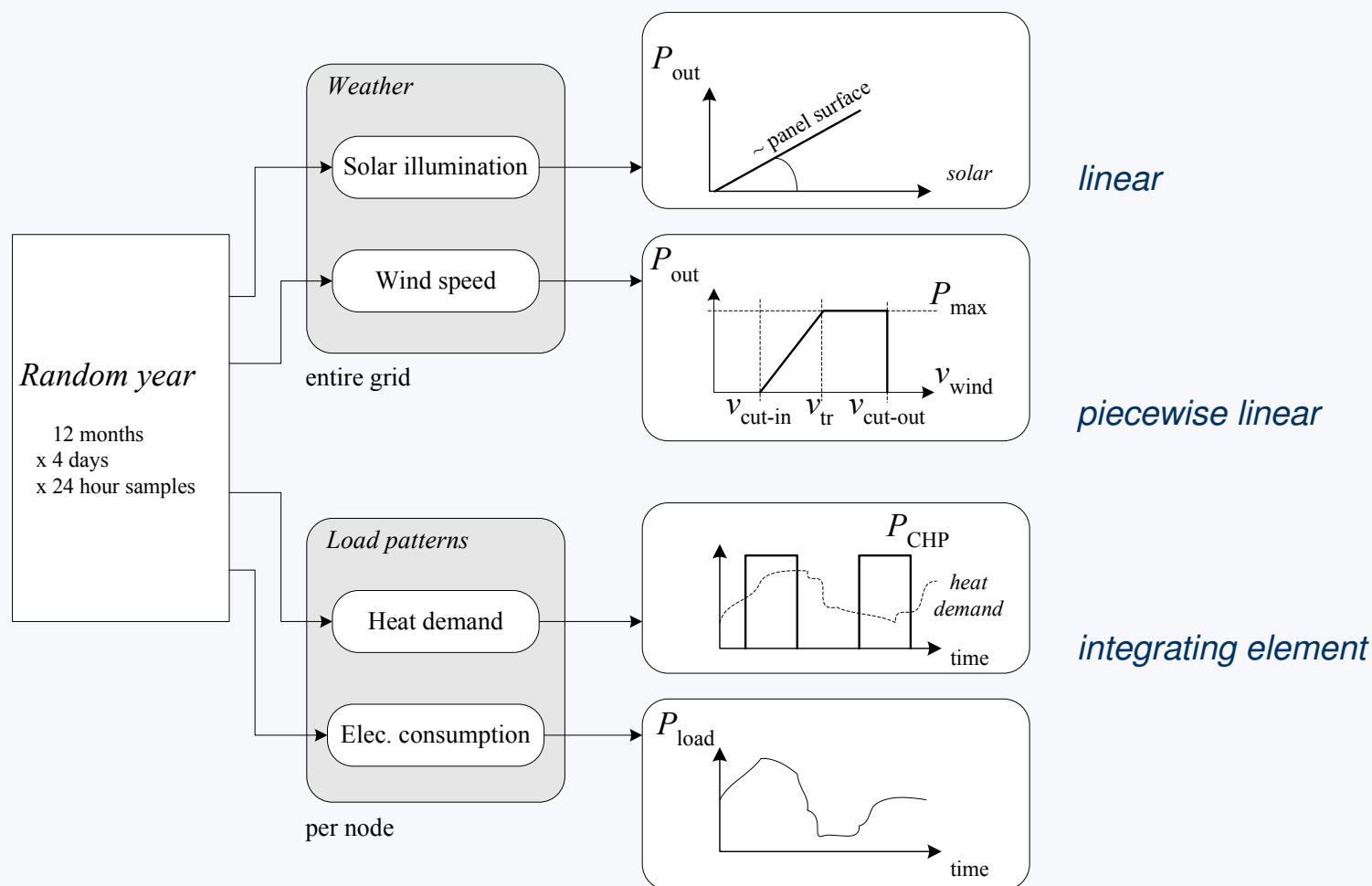
### ➤ Pareto optimality fitness $\sim$ Pareto ranking

*set-oriented*  
*scaling-independent*



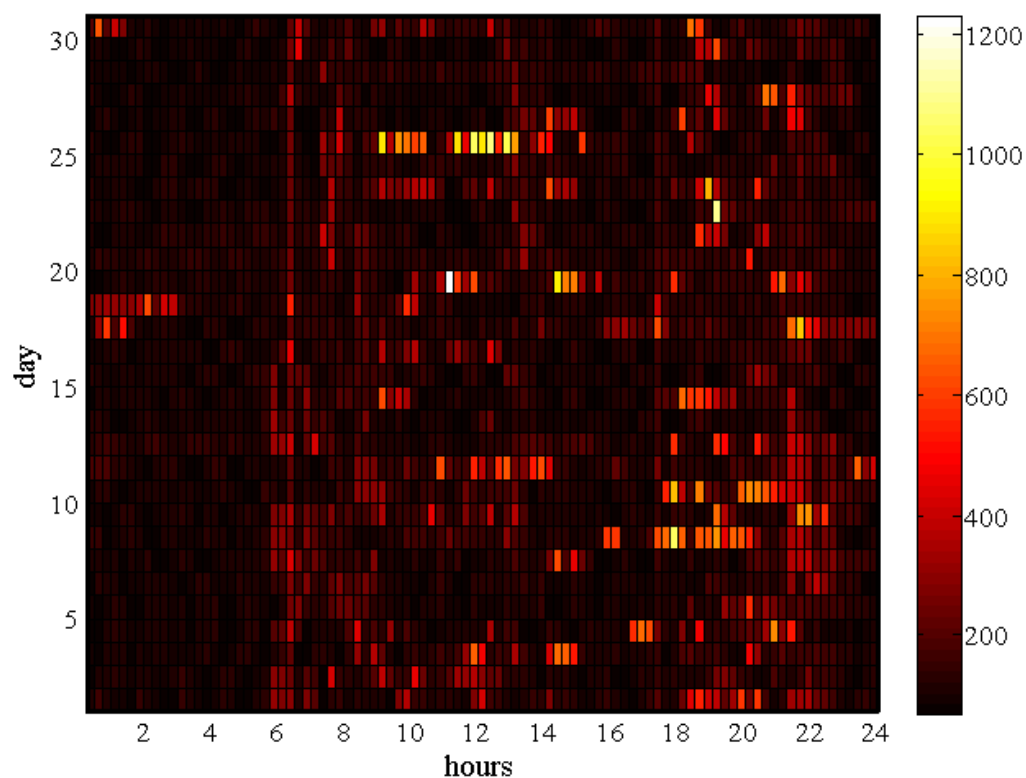


# Stochastic GA input



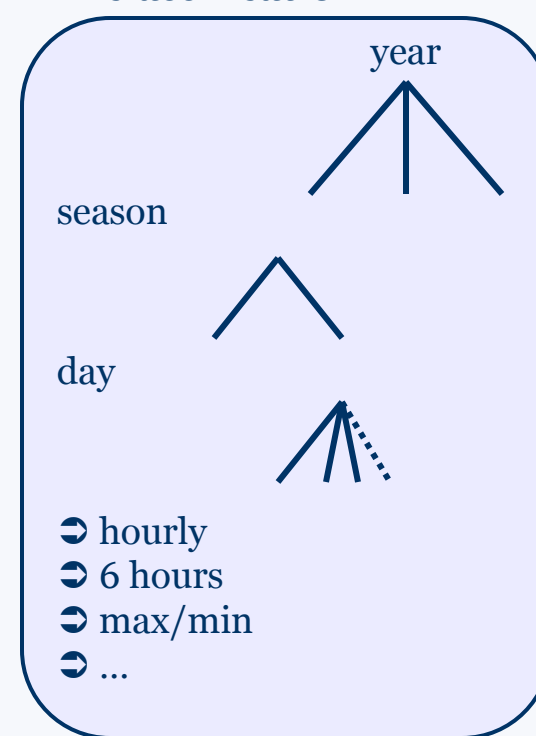
⇒ **historical data needed!!**

## Modeling of load profiles



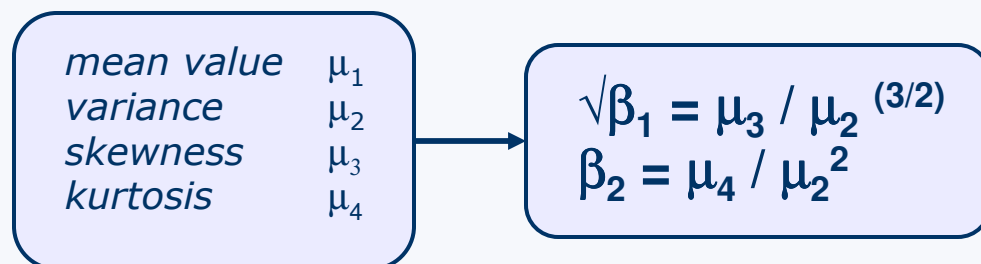
residential load during May – 15min samples (Wh)

### classification



## Pearson generalized functions

- Probability density function fitting of empirical data
- pdf is characterized by the first 4 moments
- $(\beta_1, \beta_2)$  indicates most appropriate function



*single residential load*

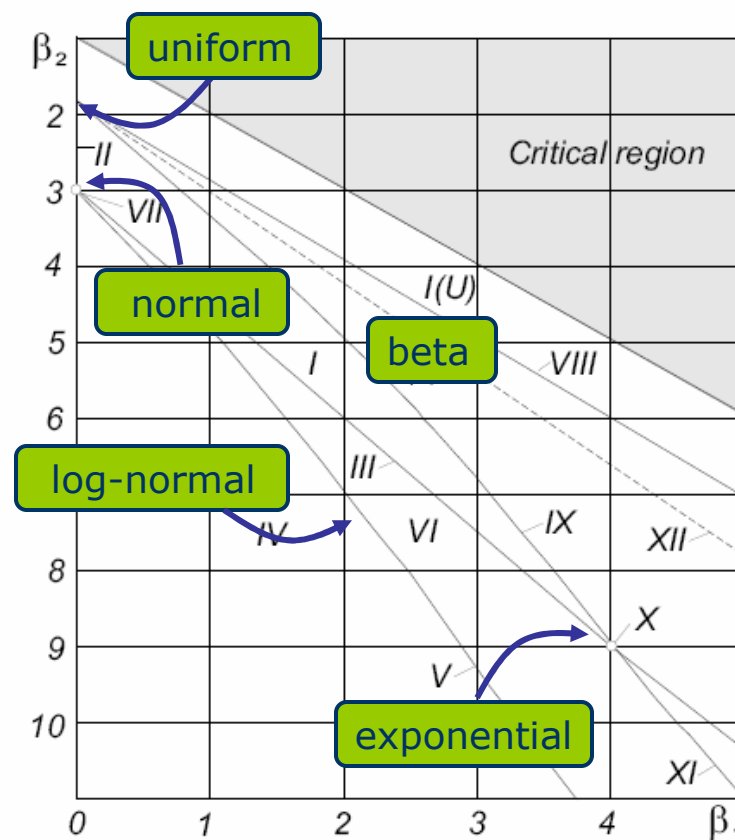
large time-frame: exponential

Short time-frame: uniform

3-hour blocks: log-normal

*aggregated loads*

normal / beta

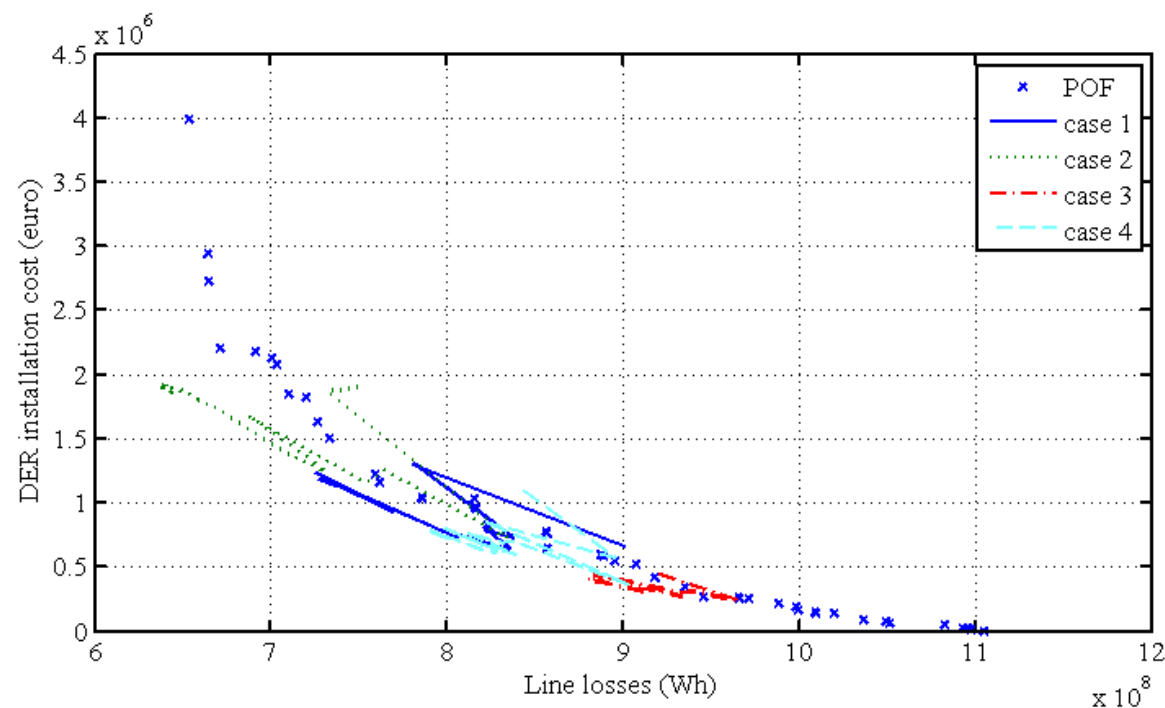


spatial/temporal load growth?!

## Heuristics

- Initial population
  - **diverse (schema theory)**
  - **deterministic optimization**
- Chromosome structure and crossover
  - **numbering**
  - **multiple crossover points**
- Mutation
  - **not random**
  - **3 operators**
    - » **Creation/deletion**
    - » **Resizing**
    - » **Location switching**
- Convergence

# Stochastic GA search pattern



## Two objectives

⇒ **DER cost**

⇒ **Line losses (NPV)** ⇒ **DER lifetime? Interest rate**

- ⇒ Chaotic search of aggregated objective
- ⇒ Slower convergence of SPEA

	$i = 8\%$	$i = 5\%$
$n = 10$ years	case 1	case 2
$n = 20$ years	case 3	case 4



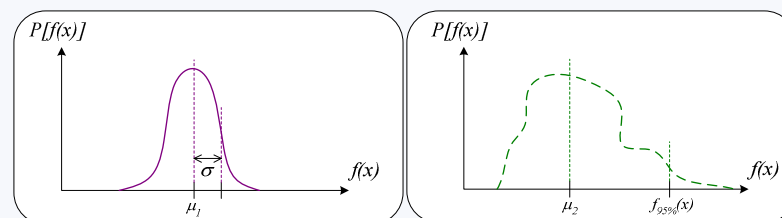
## Attributes

□ **Deterministic**  
straightforward

□ **Stochastic**  
percentile values

□ **Fuzzy**  
in final decision making

□ **Uncertain → risk**  
scenario approach: e.g. minimal regret



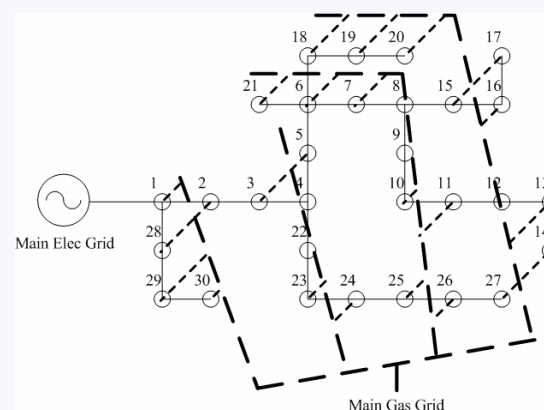
- Decision making strategies  
 'popular' techniques: e.g. fuzzy logic, game theory  
*(out of scope)*

- Pareto Front Analysis

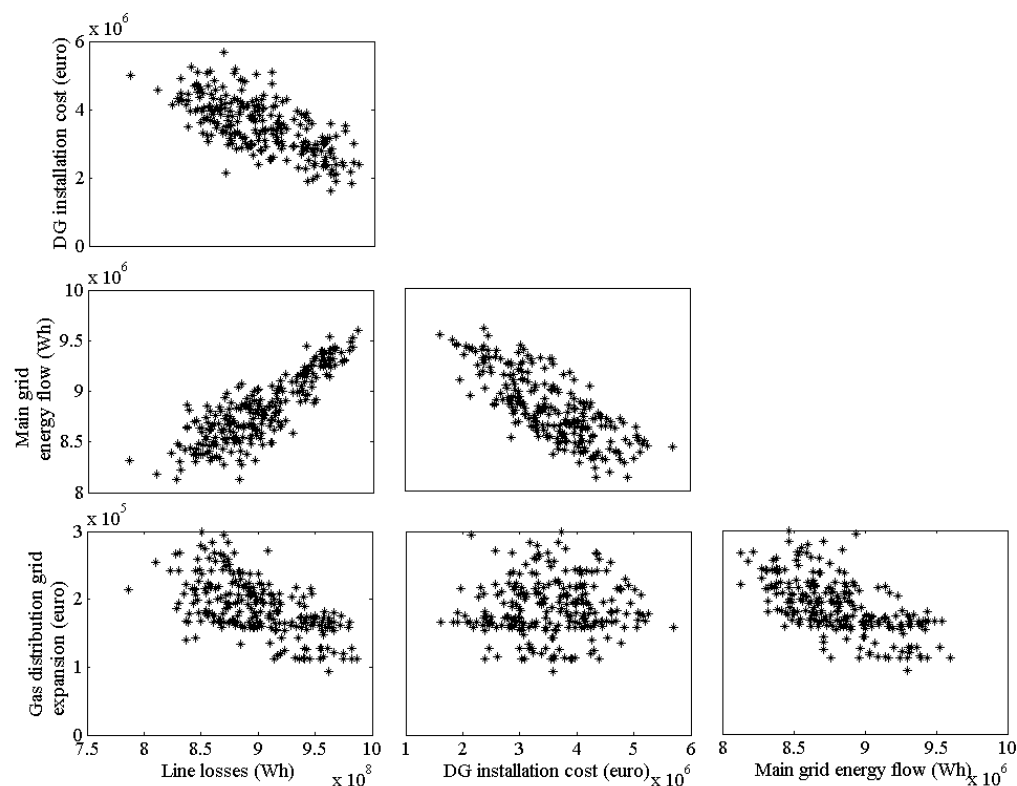
**test case:**

- » 30 bus electricity grid
- » non-fully deployed gas distribution grid
- » integration of PV panels & micro-CHP units
- » minimize {line losses, electric energy import,  
 DER installation cost, gas grid investment}

**conflicting, related, uncorrelated objectives?**



# Stochastic GA output



- two objectives  $\Rightarrow$  simple visualization
- $\geq 3 \Rightarrow ?$
- ➔ Identify strongest trade-offs

## Principal Component Analysis

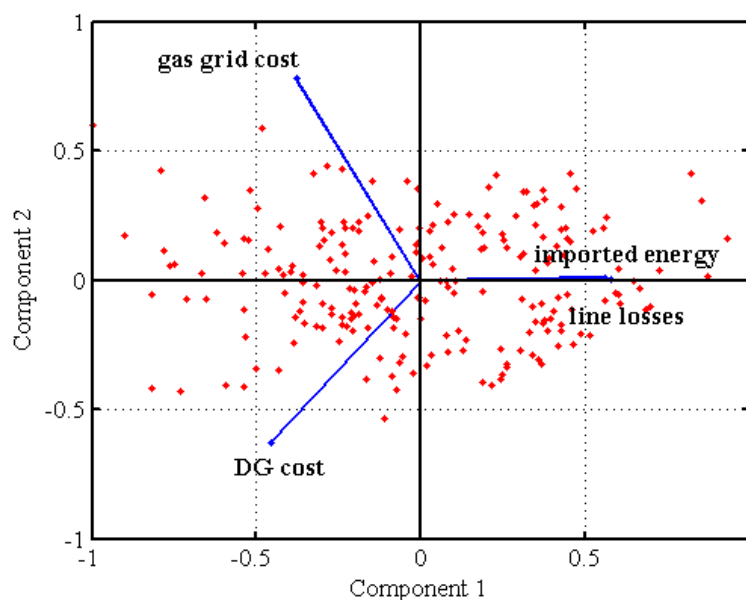
→ Reduce #dimensions of the Pareto set  $S$

→  $S = [s_1 \ s_2 \ \dots \ s_n]$

$= L \ P^T \Rightarrow P$  is set of eigenvectors of  $\text{cov}(S \ S^T)$

$= l_1 p_1 + l_2 p_2 + \dots + l_n p_n$

$\approx l_1 p_1 + l_2 p_2 \rightarrow$  principal components causing the largest spreading of  $S$

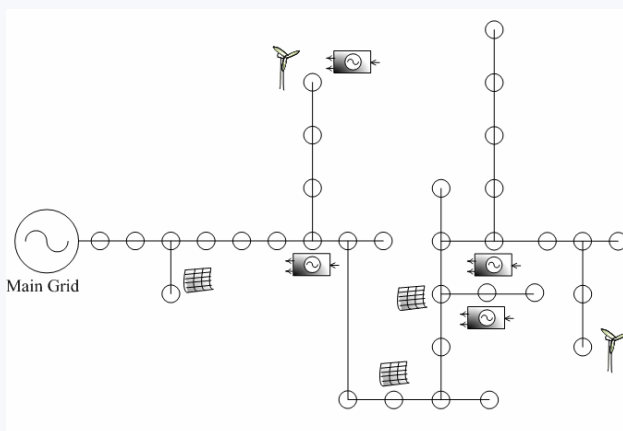
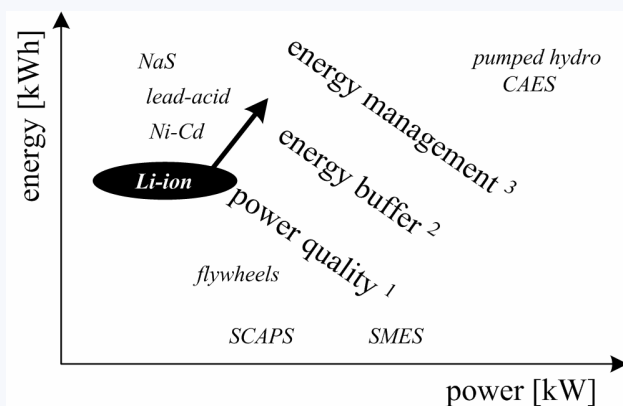


☑ 2 out of 4 objectives coincide  
 $\Rightarrow$  3 real attributes

☑ improvement in two attributes  
 = degradation of third

# Example storage unit integration

## Integration of small-scale Li-ion battery units in a LV grid with DG



### Variables

battery power & energy rating  
operation mode: threshold prices at balancing market

### Objectives

- ☑ Installation cost (*min*)
- ☑ Voltage deviation (*min*)
- ☑ Energy dependence (*min*)
- ☑ Line losses (*min*)
- ☑ Conversion losses (*min*)
- ☑ Revenue at balancing market (*max*)

### Loads

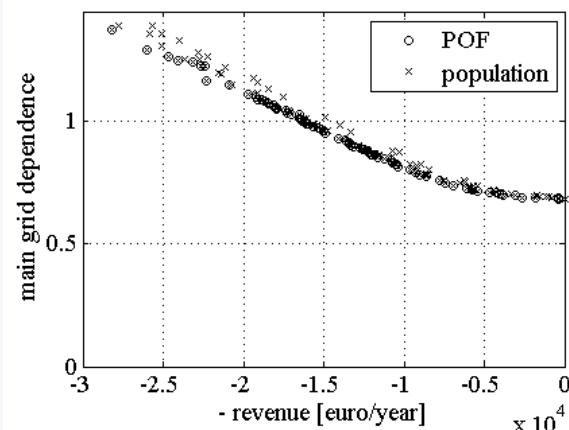
residential/commercial

### DG

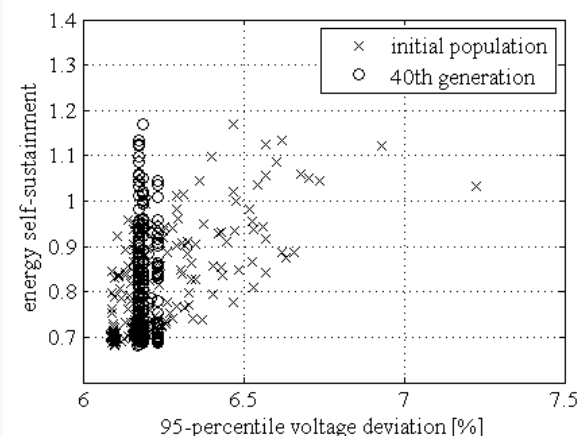
wind turbines  
PV panels  
micro-CHP

# Example

## storage unit integration

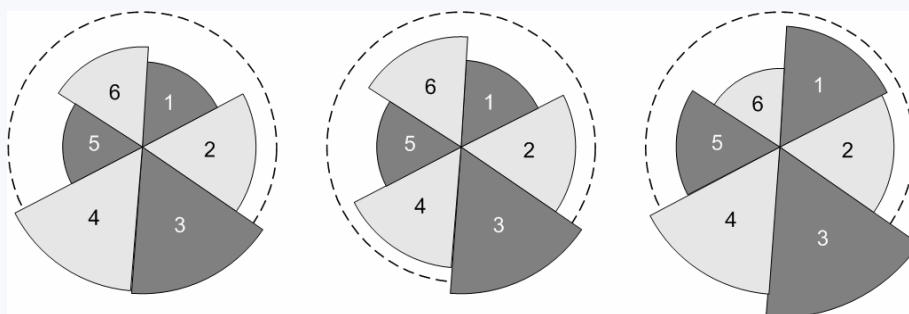


- Revenue maximization
- Energy dependence ( $= 1 - E_{\text{import}}/E_{\text{load}}$ )
  - Wide trade-off
  - No perfect match DG-load



- Voltage deviations (95-percentile)
- Energy dependence
  - correlation
  - accuracy improvement visible

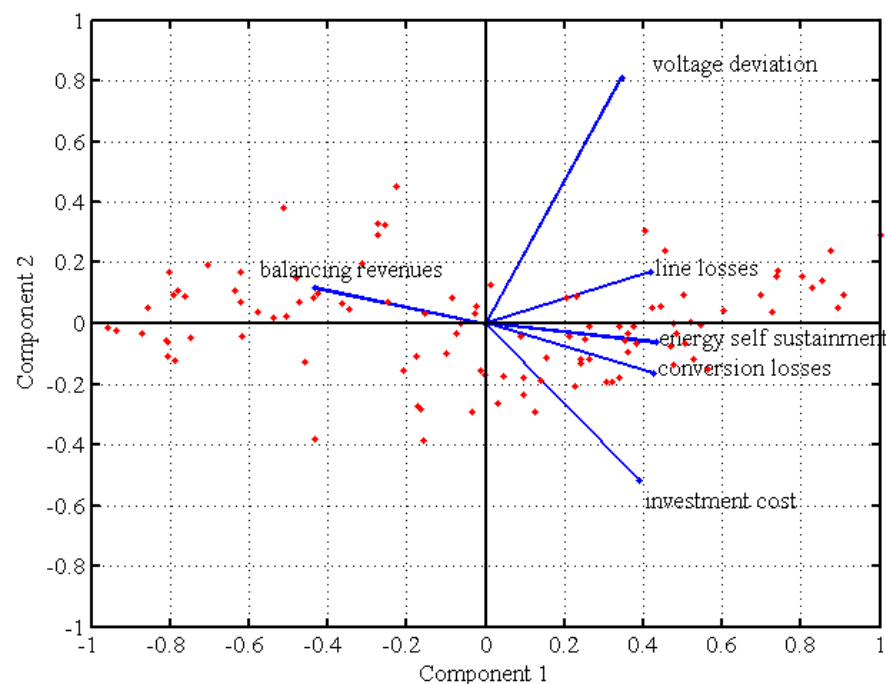
# Example storage unit integration



## Petal diagrams

visualize

- ☐ multiple
- ☐ normalized criteria
- ☐ of specific solutions



## Principal Component Analysis



**Determine optimal allocation of  
storage energy for**

- ☐ *balancing revenues*
- ☐ *ancillary services*
- ☐ *energy independence*
- ☐ ...

Long-term DER planning is analyzed

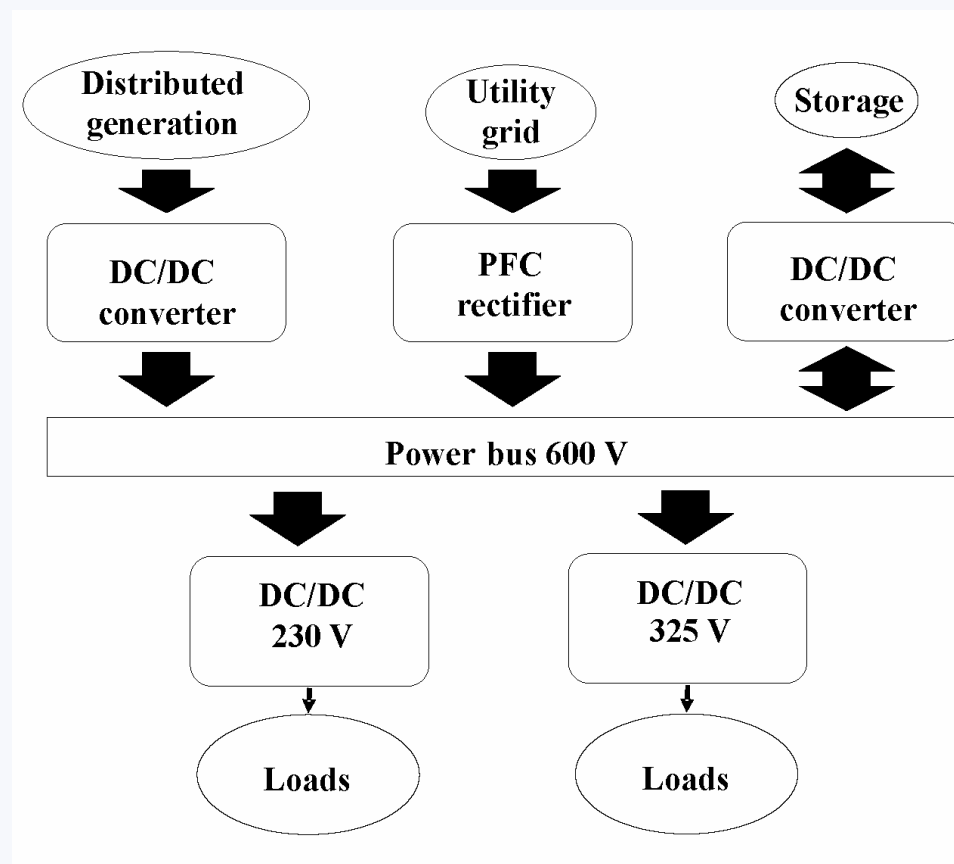
- Traditional optimization
  - ⇒ deterministic
- A new planning scheme is proposed
  - ⇒ Multi-objective: search for trade-offs
  - ⇒ Robust: nested MC trials in an evolutionary algorithm
- Convex vs. non-convex: *No free lunch*





- ⇒ Dispatchable DER sources: link to (short-time) control
  - **Gas turbines, Storage units (accepted CIRED paper)**
  - **Short-term planning vs. long-term planning**
  
- ⇒ Stability issues
  - **grid reliability**
  
- ⇒ Deterministic planning
  - **useful for initialization, convergence check**

- Many DG unit have a power electronic front-end performing a DC/AC conversion
- Many loads (power supplies) contain a AC/DC
- Connect using a DC-connection?



# Why (not) DC?



- Advantages of DC

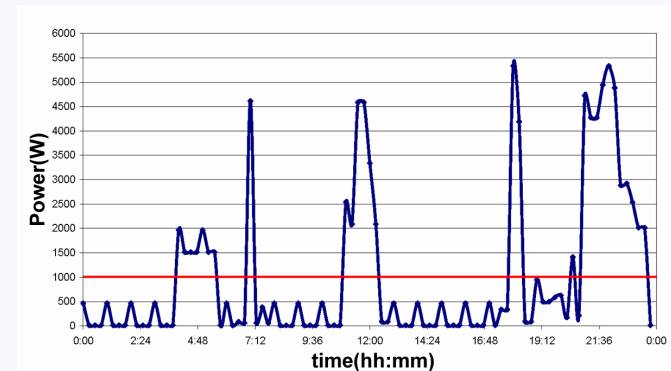
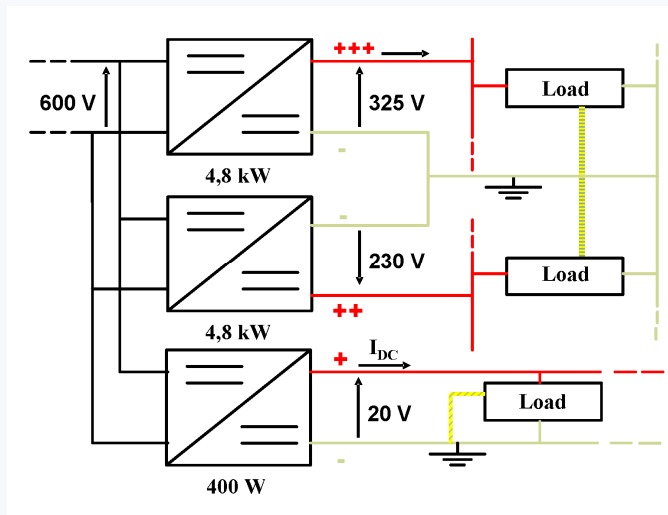
- ➔ Better use of conductors (no skin effect/proximity effect)
- ➔ No reactive power
- ➔ Only resistive voltage drops
- ➔ Lower transfer losses
- ➔ No standards yet: voltage choice still open

- Disadvantages of DC

- ➔ More dangerous in case electrocution?
- ➔ Hard to interrupt in switchgear
- ➔ No large rotating generators (do we need them?)
- ➔ More corrosive
- ➔ Standardized equipment for AC

- Edison started that way
- On-board vehicles: DC grid
- Several experiments around the world, e.g. Japan
  - ➔ KUL proposal (IECON06 paper)

- Model of a house was derived and assessed for several layouts and voltages levels
- Simulations of daily cycles



- Only small increase in efficiency
  - ⇒ AC in-house grids already have low losses
- Safety issues can be solved
  - ⇒ Appropriate grounding
  - ⇒ Switches still necessary with most loads 'always on'?
- Problem is relatively bad partial load efficiency of DC/DC converters
  - ⇒ Push for advanced designs?

*Thank you for your attention!*

*Questions?*

